5.4.3.1

Delay Line Performance Standard Validation Problem

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I. Introduction

This standard validation problem concerns the performance of a delay line on a printed circuit board. Signal traces are often created in various serpentine shapes to lengthen the trace length and achieve a desired delay. The coupling between the legs of the serpentine delay line can create significant distortion in the pulse, which is not simulated in typical transmission line based simulation tools. The distortion can easily cause timing problems as well as create common mode currents, which can cause EMC problems.

II. Problem Description

Two different configurations have been modeled here. Firstly a board on which a meander delay line is printed is considered. Fig.1 shows the geometry for this problem. Secondly, a board on which a straight line whose length is equal to that of the meander line is considered. This is referred s equivalent length straight line and it is shown in Fig.2. For both configurations the excitation source is a voltage pulse of trapezoidal shape.

For both configurations the following have been computed and compared.

- The transient voltage waveform across the load termination
- The electric field in frequency domain computed on a plane, parallel to the board, at 2 cm above the dielectric
- The signal distortion at the end of the lines defined as the pulse time delay and the ratio of the peak values

The analysis has been performed in the frequency range 50 MHz – 5GHz.

PCB Dimensions and Materials

Meander Delay Line Model (see Fig.1) - The PCB model has is constructed as follows. The reference plane is made of Perfect Electric Conductor (PEC) material whose dimensions are 23.25mm x 40.25mm x 0.2mm (x, y, z axis). Over the metal plane a dielectric substrate made of FR4 with dielectric permittivity of $\varepsilon_r = 4.7$ and of dimensions are 23.25mm x 40.25mm x 0.25mm is placed. No dielectric losses are considered. The meander trace, made of PEC, is placed on the dielectric substrate and like a serpentine, it has number of closely coupled legs. The dimensions of the trace are 0.25mm wide, 0.2mm thick and 0.25mm legs separation. The trace is simulated as a PEC material. The characteristic impedance of the line is 56Ω.

Equivalent Length Straight Line Model (see Fig.2) –
- The PCB model has is constructed as follows. The reference plane is made of Perfect Electric Conductor (PEC) material whose dimensions are 183.25mm x 40.25mm x 0.2mm (x, y, z axis). Over the metal plane a dielectric substrate made of FR4 with dielectric permittivity of $\varepsilon_r = 4.7$ and of dimensions are 183.25mm x 40.25mm x 0.25mm is placed. No dielectric losses are considered. A straight trace made of PEC is placed on the dielectric substrate. The characteristic impedance of the line is 50 Ω.
### Source / Load Termination

**Meander Delay Line Model** – The trace is driven against the reference plane by a trapezoidal voltage pulse of amplitude equal to 1V, $t_{\text{rise}}=0.2\text{ns}$, $t_{\text{fall}}=0.2\text{ns}$, and $t_{\text{hold}}=1\text{ns}$, as shown in Fig. 3a. The length of the considered time window is 10ns as shown in Fig. 3b. By applying a Fast Fourier Transform (FFT) the frequency spectrum of the magnitude of the voltage pulse is computed and shown in Fig. 3c. The load termination (at the receiver end, see Fig. 1a) is a resistive impedance equal to the characteristic impedance of the line $Z_{\text{load}} = 56\Omega$. The internal impedance of the voltage source (driver end, see Fig. 1a) is set $Z_{\text{source}} = 0\Omega$. The structure is excited with a voltage discrete port [2].

**Equivalent Length Straight Line Model** - The trace is driven against the reference plane by a trapezoidal voltage pulse of amplitude equal to 1V, $t_{\text{rise}}=0.2\text{ns}$, $t_{\text{fall}}=0.2\text{ns}$, and $t_{\text{hold}}=1\text{ns}$, as shown in Fig. 3a. The length of the considered time window is 10ns as shown in Fig. 3b. By applying a Fast Fourier Transform (FFT) the frequency spectrum of the magnitude of the voltage pulse is computed and shown in Fig. 3c. The load termination (at the receiver end, see Fig. 1a) is a resistive impedance equal to the characteristic impedance of the line $Z_{\text{load}} = 50\Omega$. The internal impedance of the voltage source (driver end, see Fig. 1a) is set $Z_{\text{source}} = 0\Omega$. The structure is excited with a voltage discrete port [2].

### III. Model’s details

To perform the numerical calculations, the Finite Integration Technique (FIT) [1, 2] is used.

Fig.4a shows the position of the source and load in the meander delay line model. To model the voltage source that is applied between the metal plane and the trace, a discrete port has been used. To model a load termination of 56 $\Omega$ a lumped element [2] has been used, as described in Fig.4b and Fig.4c. Fig.5a shows the excitation source and load used in the equivalent length straight line model. To model the voltage source applied between the metal plane and the trace a discrete port has been used. A discrete port is used to model the 50 $\Omega$ load terminations, as illustrated in Fig.5b and Fig.5c.

The frequency spectrum of the magnitude of the electric field on a plane 2 cm over the dielectric substrate has been computed in the frequency range of 50 MHz to 5GHz. The observation points (or probes) $P_i$ of the electric field are separated one to the other by a separation distance of 10 mm. In each observation point the three components of the electric field along the x, y and z axis are computed.

For the meander delay line model a set of 15 observations points are selected and placed as in Fig. 6a. For the equivalent length straight line model a set of 25 observations points are selected and placed as shown in Fig.6b. The boundary conditions are set as illustrated in Fig.7.
IV. Results

Fig. 8 shows the comparison between the transient voltage waveforms at the receiver end for meander delay line and equivalent length straight line.

At each observation point $P_i$ of the meander delay line or equivalent length straight line, the transient waveform of the three spatial components $\alpha = x, y, z$ of the electric field $E_{\alpha}(t, P_i)$ are numerically evaluated. Fig. 9 shows the comparison of the transient waveform of the main component (along the $z$ axis) of the electric field $E_z(t, P_i)$, evaluated at the center probe for both the meander delay line (Fig. 6a) and the equivalent length straight line (Fig. 6b) configurations. Each transient field $E_{\alpha}(t, P_i)$ is transformed in frequency domain by means of a Fast Fourier Transform (FFT).

$$E_{\alpha}(t, P_i) \rightarrow FFT \rightarrow E_{\alpha}(\omega, P_i) \quad (1)$$

Fig. 10 shows the comparison of the frequency spectra of $|E_z(\omega, P_i)|$ of Fig. 9 computed for both the configurations. The magnitude of the total electric field at each frequency and at each of the observation points $P_i$ is computed as

$$|E(\omega, P_i)| = \sqrt{|E_x(\omega, P_i)|^2 + |E_y(\omega, P_i)|^2 + |E_z(\omega, P_i)|^2} \quad (2)$$

Fig. 11 shows the frequency spectrum from 50 MHz to 5 GHz of the magnitude of the total electric field due to the trapezoidal source in Fig. 3, computed as in (2) for each of the 15 observation points of Fig. 6a for the meander delay line.

Fig. 12 shows the frequency spectrum from 50 MHz to 5 GHz of the magnitude of the total electric field due to the trapezoidal source in Fig. 3, computed as in (2) for each of the 25 observation points of Fig. 6b for the equivalent length straight line.

The maximum values of the magnitude of the total electric field from 50 MHz to 5 GHz are -160.212dBV/m among all the observation points of the meander delay line and -171.143dBV/m for the equivalent length straight line respectively.

For each configuration, distortion has been defined by using the following figures of merit:

- the propagation delay time $T_d$ defined as (see Fig. 13 and Fig. 14):

$$T_d = t_2 - t_1$$

$t_1$ being the time at which the input voltage crosses for the first time its half value and $t_2$ being the time at which the voltage at termination load crosses its half value. The results is are tabulated in TABLE I.
• the ratio between the maximum value of the output voltage $V_{OUT}(t)$ and the maximum value of the input voltage $V_{IN}(t)$:

$$\frac{\text{MAX}(V_{OUT}(t))}{\text{MAX}(V_{IN}(t))}, \quad 0 \leq t \leq 10\text{ns}$$

Where, $V_{OUT}(t)$ is the voltage across the load termination and $V_{IN}(t)$ is the voltage across the source termination see Fig.3). The results are tabulated in TABLE I.

**TABLE I - TIME DELAY AND PEAK RATIO**

<table>
<thead>
<tr>
<th></th>
<th>$T_d = t_2 - t_1 [\text{ns}]$</th>
<th>$\frac{\text{MAX}(V_{OUT}(t))}{\text{MAX}(V_{IN}(t))}$, $0 \leq t \leq 10 \text{ ns}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meander Delay Line</td>
<td>0.7524</td>
<td>1.321</td>
</tr>
<tr>
<td>Equivalent Length</td>
<td>0.9923</td>
<td>0.9559</td>
</tr>
<tr>
<td>Straight Line</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**V. Data Sets**

The transient voltage waveforms of the source and across the load terminations for the two configurations are stored in the following files:

- `V_M_source.txt` → source voltage
- `V_M_load.txt` → load voltage (across 56 $\Omega$)
- `V_S_source.txt` → source voltage
- `V_S_load.txt` → load voltage (across 50 $\Omega$)

In which `M` stands for “Meander delay line” and `S` stands for “equivalent length Straight line”.

In each observation point $P_i$ of both models, three probes have been placed to record the three transient spatial components of the electric field $E_\alpha(t,P_i)$ with $\alpha = x, y, z$ respectively.

For the meander delay line the transient waveforms of the electric field are stored in the files named:

- `Px_M_ij.txt` → x component
- `Py_M_ij.txt` → y component
- `Pz_M_ij.txt` → z component

In which `M` stands for “Meander delay line” and $i = 1, .., 3$ and $j = 1, .., 5$ identify the position of the probes according to the index shown in Fig. 15.

For the equivalent length straight line the transient waveforms of the electric field are stored in the files named:

- `Px_S_hk.txt` → x component
- `Py_S_hk.txt` → y component
Pz_S_hk.txt → z component

In which S stands for “equivalent length Straight line” and h = 1, .., 5 and k = 1, .., 5 identify the position of the probes according to the index shown in Fig. 16.

On request (orlandi@ing.univaq.it) the CST STUDIO SUITE 2006 [2] models used for the simulations are available. The file names are as follows.

1) Meander Delay Line  →  Archive: 5.4.3.1_Meander
2) Straight length trace  →  Archive: 5.4.3.1_Straight
Fig. 1a - Meander delay line (Top View).

Fig. 1b - Meander delay line cross section (View A).
Fig. 2a – Equivalent length straight line.

Fig. 2b – Equivalent length straight line cross section (View A).
Fig. 3a – Excitation pulse; $t_{\text{rise}}=0.2\text{ns}$, $t_{\text{fall}}=0.2\text{ns}$, $t_{\text{hold}}=1\text{ns}$.

Fig. 3b – Excitation pulse, Microwave studio settings.
Fig. 3c – Magnitude of the frequency spectrum of the excitation pulse (see Fig.3b).

Fig. 4a – Discrete Port as voltage source; lumped element as termination load.
Fig. 4b - Discrete Port like voltage source and Microwave Studio settings.

Fig. 4c – Lumped Element like a load termination and Microwave Studio settings.

Fig. 5a - Discrete Port like voltage source, Discrete Port like termination load.
**Fig. 5b** - Discrete Port like voltage source, Microwave Studio settings.

**Fig. 5b** - Discrete Port like load termination, Microwave Studio settings.
**Fig. 6a** – Observation points distribution (probes). Central probe is centered over the structure.

**Fig. 6b** – Observation points distribution (probes). Central probe is centered over the structure.
Fig. 7a – Meander delay line model: boundary conditions settings.

Fig. 7b – Equivalent length straight line model: boundary conditions settings.
Fig. 8 – Comparison of the voltage wave shape at the receiver end for both configurations.
Fig. 9 - Transient waveforms of the main component of the electric field $E_z(t, P^i)$ computed 2 cm above the dielectric at the central probe (as in Fig. 6a and 6b) for both configurations.
**Fig. 10** - Frequency spectrum of $|E_z(\omega, P^i)|$ computed 2 cm above the dielectric at the central probe (as in Fig. 6a and 6b) for both configurations.
Fig. 11 – Magnitude of the electric field recorded in each of the 15 observation points for the meander delay line model between 50MHz and 5GHz.

\[ \text{Max } |E(\omega, P)\| = -160.212 \text{ dBV/m} \]
Fig. 12 – Magnitude of the electric field recorded in each of the 25 observation points for the equivalent length straight line model between 50MHz and 5GHz.

\[
\text{Max } |E(\omega, P_i)| = -171.143\text{dBV/m}
\]

Fig. 13 – Delay time for meander delay line.
Fig. 14 – Delay time for equivalent length straight line.
**Fig. 15** – Meander delay line: some probe’s coordinates.

**Fig. 16** – Equivalent length straight line: some probe’s coordinates.
References

